WSU–HEP–XXYY
September 1, 2015

Studies of Charmonium at BESIII

Rong-Gang Ping

Institute of High Energy Physics,Chinese Academy of Sciences, PO BOX 918(1), Beijing 100049

Based on $\psi(3686)$ decays of 106 million, the 1.31 billion J/ψ events and a data sample of $\psi(3770)$ with 2.9 fb^{-1} integrated luminosity, many analyses are performed. Exclusively baryonic decays of the $\psi(3770)$, the radiative transition $\psi(3770) \to \gamma\eta_c(2S)$, the $\psi(3770)$ transition to χ_{cJ}, isospin violation decay $\chi_{c0,2} \to \pi^0\eta_c$, the $C-$parity violation decays $J/\psi \to \gamma\gamma, \gamma\phi$ are searched for, but no significant signals are observed, and upper limits are set for these decays. The decays of $\psi(3770) \to \gamma\chi_{c1}$ and $J/\psi \to \pi^0\phi$ signals are observed. These measurements provide more information on the charmonium structure, and the isospin and C-parity violation in the charmonium decays.

PRESENTED AT

The 7th International Workshop on Charm Physics
(CHARM 2015)
Detroit, MI, 18-22 May, 2015

1 Introduction

Results in this presentation are based on data samples accumulated with the BESIII detector at the BEPCII collider, which include $\psi(3686)$ decays of 106 million, a sample of 1.31 billion J/ψ events and $\psi(3770)$ data of 2.9 fb^{-1} integrated luminosity, and 42 pb^{-1} continuum data taken at 3.65 GeV.

2 Search for $\psi(3770)$ exclusive decays

The nature of the excited $J^{PC} = 1^{--}$ $c\bar{c}$ bound states above the $D\overline{D}$ threshold is of interest but still not well known. The $\psi(3770)$ resonance, as the lightest charmonium state lying above the open charm threshold, is generally assigned to be a dominant 1^3D_1 momentum eigenstate with a small 2^3S_1 admixture [1]. It has been thought almost entirely to decay to $D\overline{D}$ final states [2]. Unexpectedly, the BES Collaboration found a large inclusive non-$D\overline{D}$ branching fraction, $(14.7 \pm 3.2)\%$, by utilizing various methods [3], neglecting interference effects, and assuming that only one $\psi(3770)$ resonance exists in the center-of-mass energy between 3.70 and 3.87 GeV. A later work by the CLEO Collaboration taking into account the interference between the resonance decays and continuum annihilation of e^+e^- found a contradictory non-$D\overline{D}$ branching fraction, $(-3.3 \pm 1.4^{+6.6}_{-4.8})$. The BES results suggest substantial non-$D\overline{D}$ decays, although the CLEO result finds otherwise. Till now the observed non-$D\overline{D}$ exclusive decays sum up to less than 2% of all decays, which motivates the search for other exclusive non-$D\overline{D}$ final states.

2.1 Baryonic decays of $\psi(3770)$

By analyzing data samples of 2.9 fb^{-1} collected at $\sqrt{s} = 3.773$ GeV, the exclusive decays to final states, $\Lambda\overline{\Lambda}\pi^+\pi^-$, $\Lambda\overline{\Lambda}\pi^0$, $\Lambda\overline{\Lambda}\eta$, $\Sigma^+\overline{\Sigma}^-$, $\Sigma^0\overline{\Sigma}^0$, $\Xi^-\overline{\Xi}^+$ and $\Xi^0\overline{\Xi}^0$, are searched for [4]. The QED backgrounds are estimated with the data samples taken at $\sqrt{s}$=3.542, 3.554, 3.561, 3.600 and 3.650 GeV, and the backgrounds from the initial state radiation (ISR), e.g. $e^+e^- \to \gamma\psi(3686)$, $\gamma\psi(3770)$ are estimated with Monte-Carlo (MC) simulation. After subtraction of these backgrounds, no significant signals are observed. The upper limits at the 90% confidence level (CL) are set as $4.4, 0.7, 1.9, 1.0, 0.4, 1.5$ and 1.4 ($\times 10^{-4}$) for $\psi(3770) \to \Lambda\overline{\Lambda}\pi^+\pi^-$, $\Lambda\overline{\Lambda}\pi^0$, $\Lambda\overline{\Lambda}\eta$, $\Sigma^+\overline{\Sigma}^-$, $\Sigma^0\overline{\Sigma}^0$, $\Xi^-\overline{\Xi}^+$ and $\Xi^0\overline{\Xi}^0$, respectively.

These results provide useful information for understanding the nature of $\psi(3770)$, but the large non-$D\overline{D}$ component still remains a puzzle. A fine energy scan over $\psi(3770)$ and $\psi(4040)$ resonances would be very helpful for obtaining the lineshape of exclusive non-$D\overline{D}$ processes, and help determine whether the processes exist or not.

2.2 $\psi(3770) \to \gamma\eta_c(2S) \to \gamma K^0_S K\pi$

The radiative transitions $\psi(3770) \to \gamma\eta_c(2S)$ are supposed to be highly suppressed by selection rules, considering the $\psi(3770)$ is predominantly the 1^3D_1 state. However, due to the non-vanishing photon energy in the decay, higher multipoles beyond the leading one could contribute [5]. Experimental measurements of the branching fractions $\mathcal{B}(\psi(3770) \to \gamma\eta_c(2S)$ will be very helpful for testing theoretical predictions and providing further constraints on the immediate meson loop calculation (IML) contributions.

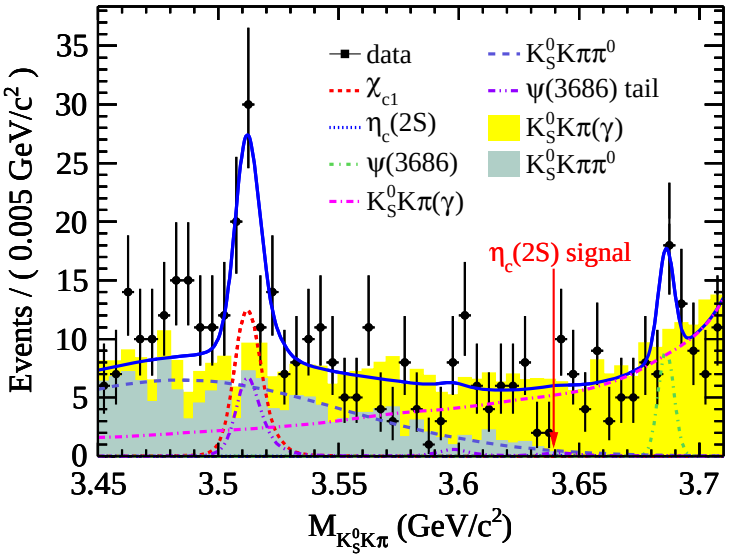

Figure 1: Invariant-mass spectrum for $K^0_S K^\pm\pi^\mp$ from data with the estimated backgrounds and best-fit results superimposed in the $\eta_c(2S)$ mass regions. Dots with error bars are data. The shaded histograms represent the background contributions. The solid lines show the total fit results.

Using the 2.92 fb^{-1} data sample taken at $\sqrt{s}$ = 3.773 GeV, searches for the radiative transitions between the $\psi(3770)$ and the $\eta_c(2S)$ through the decay process $\psi(3770) \to \gamma K^0_S K^\pm\pi^\mp$ are performed [6]. Figure 1 shows the invariant mass distribution in the $\eta_c(2S)$ mass region. No significant $\eta_c(2S)$ signals are observed. Upper limits on the branching fraction at a 90% C.L. is set as $\psi(3770) \to \gamma\eta_c(2S) \to \gamma K^0_S K^\pm\pi^\mp) < 5.6\times10^{-6}$, or $\mathcal{B}(\psi(3770) \to \gamma\eta_c(2S)) < 2.0\times10^{-3}$.

The measured branching fraction corresponds to the partial decay width 55 KeV, which is larger than the prediction of the IML [5] (0.6 ∼3.8 KeV). This is due to the limitation by statistics and the dominant systematic error, which stems from the uncertainty in the branching fraction of $\eta_c(2S) \to K^0_S K^\pm\pi^\mp$.

2.3 $\psi(3770) \to \gamma\chi_{cJ}$

Within an S-D mixing model, the $\psi(3770)$ resonance is assumed to be predominantly the 1^3D_1 $c\bar{c}$ state with a small admixture of the 2^3S_1 state. Based on this assumption, the partial widths of $\psi(3770)$ $E1$ radiative transitions are predicted with large uncertainties [7]. Precision measurements of partial widths of the $\psi(3770) \to \gamma\chi_{c1,2}$ processes are critical to test the above mentioned models, and to better understand the nature of the $\psi(3770)$, as well as to find the origin of the non-$D\overline{D}$ decays of the $\psi(3770)$.

By analyzing 2.92 fb^{-1} of data collected at $\sqrt{s} = 3.773$ GeV, the decay $\psi(3770) \to \gamma\chi_{c1}$ was searched for [8], and the χ_{cJ} candidates are reconstructed with the decay $\chi_{cJ} \to \gamma J/\psi$. Figure 2 shows the invariant mass spectrum of the energetic photon and J/ψ. The decays to χ_{c1} are observed, while no significant signal for the χ_{c2}. The branching fraction is measured to be $\mathcal{B}(\psi(3770) \to \gamma\chi_{c1}) = (2.48 \pm 0.15 \pm 0.23) \times 10^{-3}$ and a 90% C.L. upper limit $\mathcal{B}(\psi(3770) \to \gamma\chi_{c2}) < 0.64 \times 10^{-3}$. This measured branching fraction for $\psi(3770) \to \gamma\chi_{c1}$ is consistent within error with $\mathcal{B}(\psi(3770) \to \gamma\chi_{c1}) = (2.8 \pm 0.5 \pm 0.4) \times 10^{-3}$ measured by CLEO-c [9], but the precision of this measurement is improved by more than a factor of 2.

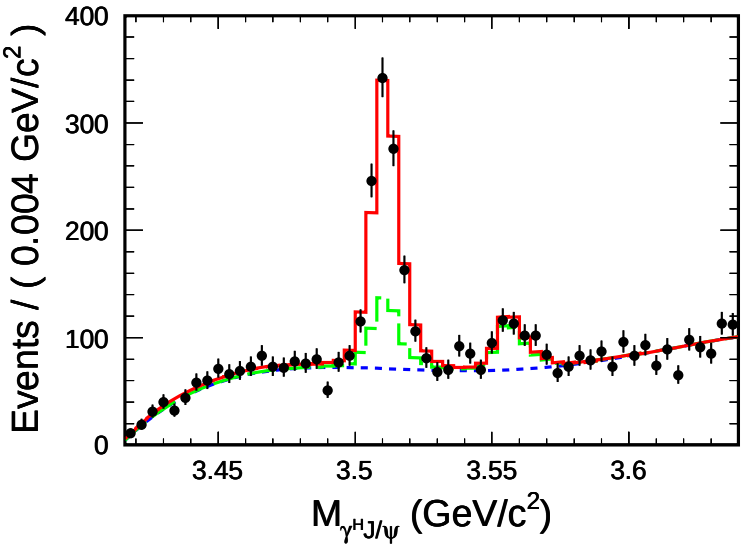

Figure 2: Invariant mass spectrum of the energetic photon and J/ψ combinations selected from data. The dots with error bars represent the data. The solid (red) line shows the fit. The dashed (blue) line shows the smooth background. The long-dashed (green) line is the sum of the smooth background and the contribution from $e^+e^- \to (\gamma_{\rm ISR})\psi(3686)$ production.

3 Searches for isospin-violating transitions $\chi_{c0,2} \to \pi^0\eta_c$

Isospin is known to be a good symmetry in the hadronic decays of charmonium states. The decay rates of isospin-symmetry breaking modes are in general found to be very small. However, the isospin transition $\psi(3686) \to \pi^0 J/\psi$ is observed with large branching fraction; the ratio $\mathcal{B}(\psi(3686) \to \pi^0 J/\psi)/\mathcal{B}(\psi(3686) \to \eta J/\psi)$ is measured to be 0.374 ± 0.072 [10], which indicates the important role played by the nonperturbative effects [11]. Searches for the isospin decay $\chi_{cJ} \to \pi^0\eta_c$ gives insights in the isospin-violating mechanisms.

An analysis was performed with the aim to search for the hadronic isospin-violating transitions $\chi_{c0,2} \to \pi^0\eta_c$ using 106×10^6 $\psi(3686)$ events collected by BESIII through $\eta_c \to K^0_S K^\pm\pi^\mp$ decays [12]. No statistically significant signal is observed and upper limits on the branching fractions for the processes $\chi_{c0,2} \to \pi^0\eta_c$ have been obtained. The results are $B(\chi_{c0} \to \pi^0\eta_c) < 1.6 \times 10^{-3}$ and $B(\chi_{c2} \to \pi^0\eta_c) < 3.2 \times 10^{-3}$. These are the first upper limits that have been reported so far. These limits might help to constrain nonrelativistic field theories and provide insight in the role of charmed-meson loops to the various transitions in charmonium and charmonium-like states. Further developments in these theories will be necessary to clarify this aspect.

The obtained upper limit on $B(\chi_{c0} \to \pi^0\eta_c)$ does not contradict the theoretical estimate of order (few)$\times 10^{-4}$ [13] . In addition, the branching fractions of the hadronic decays $\chi_{c0} \to \pi^0\eta_c$ and $\chi_{c1} \to \pi^+\pi^-\eta_c$ are predicted approximately equal [13]. An earlier theoretical estimate in the framework of a QCD multipole expansion [15] reported a branching fraction for $\chi_{c1} \to \pi\pi\eta_c$ of (2.22$\pm$1.24)%, which contradicts the earlier BESIII measurement [14] and, under the above relation [13], this measurement as well.

4 Search for $C-$violation decay $J/\psi \to \gamma\gamma, \gamma\phi$

In the Standard Model (SM), C-invariance is held in strong and electromagnetic (EM) interactions. Until now, no C-violating processes have been observed in EM interactions [16]. While both C-parity and P-parity can be violated in the weak sector of the electroweak interactions in the SM, evidence for C violation in the EM sector would immediately indicate physics beyond the SM.

Using 1.06×10^8 $\psi(3686)$ events recorded in e^+e^- collisions at $\sqrt{s} = 3.686$ GeV, we performed searches for the C-violation decays $J/\psi \to \gamma\gamma$ and $J/\psi \to \gamma\phi$ using transition $\psi(3686) \to \pi^+\pi^- J/\psi$ [17]. The ϕ candidates are reconstructed with the decay $\phi \to K^+K^-$. The signals for $J/\psi \to \gamma\gamma$ are searched for by looking for the J/ψ candidates in the recoil mass distribution $M_{\pi^+\pi^-}$, while signals for $J/\psi \to \gamma\phi$ are searched for by looking for the ϕ candidates in the invariant mass $M_{K^+K^-}$.

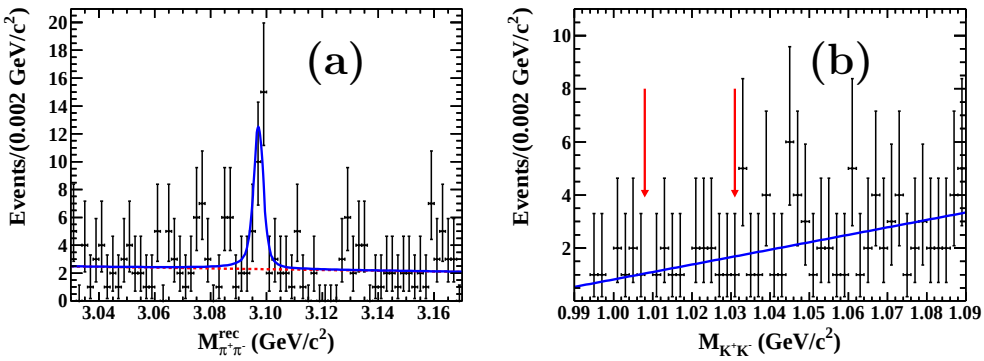

Figure 3: (a) The $M^{\rm rec}_{\pi^+\pi^-}$ distribution for $\psi(3686) \to J/\psi\pi^+\pi^-, J/\psi \to \gamma\gamma$ candidate events from data. (b) The $M_{K^+K^-}$ distribution for $\psi(3686) \to J/\psi\pi^+\pi^-, J/\psi \to \gamma\phi, \phi \to K^+K^-$ candidate events from data. The solid line shows the global fit results and the dashed line shows the background.

No significant signals are observed as shown in Fig. 3. We set the upper limits $\mathcal{B}(J/\psi \to \gamma\gamma) < 2.7 \times 10^{-7}$ and $\mathcal{B}(J/\psi \to \gamma\phi) < 1.4 \times 10^{-6}$ at the 90% C.L. for the branching fractions of J/ψ decays into $\gamma\gamma$ and $\gamma\phi$, respectively. The upper limit on $\mathcal{B}(J/\psi \to \gamma\gamma)$ is one order of magnitude more stringent than the previous upper limit, and $\mathcal{B}(J/\psi \to \gamma\phi)$ is the first upper limit for this channel. Our results are consistent with C-parity conservation of the EM interaction.

5 Search for the OZI-suppressed decay $J/\psi \to \pi^0\phi$

The J/ψ hadronic decays proceed via the $c\bar{c}$ quarks annihilation into gluons, and then they materialize into light hadrons. Thus the J/ψ is characterized by the narrow decay width, which is known as the Okubo-Zweig-Iizuka (OZI) suppressed decay [18]. A full investigation of J/ψ decaying to a vector meson (V) and a pseudoscalar meson (P) can provide rich information about SU(3) flavor symmetry and its breaking, probe the quark and gluon content of the pseudoscalar mesons, and determine the electromagnetic amplitudes [19]. For the $J/\psi \to \pi^0\phi$, the partial decay width is even more suppressed due to no quark correlation in the final states, which is regarded as double OZI (DOZI) decay. Well established phenomenological models [20] have indicated that the DOZI amplitude can have a large impact through interference with the singly OZI suppressed amplitude. To search for the decay $J/\psi \to \phi\pi^0$ is helpful for us to understand the electromagnetic DOZI mechanisms of non-ideal $\omega - \phi$ mixing [20, 21].

Based on 1.31 billion J/ψ events, we performed an analysis of the decay $J/\psi \to \phi\pi^0 \to K^+K^-\gamma\gamma$ and find a structure around 1.02 GeV/c^2 in the K^+K^- invariant

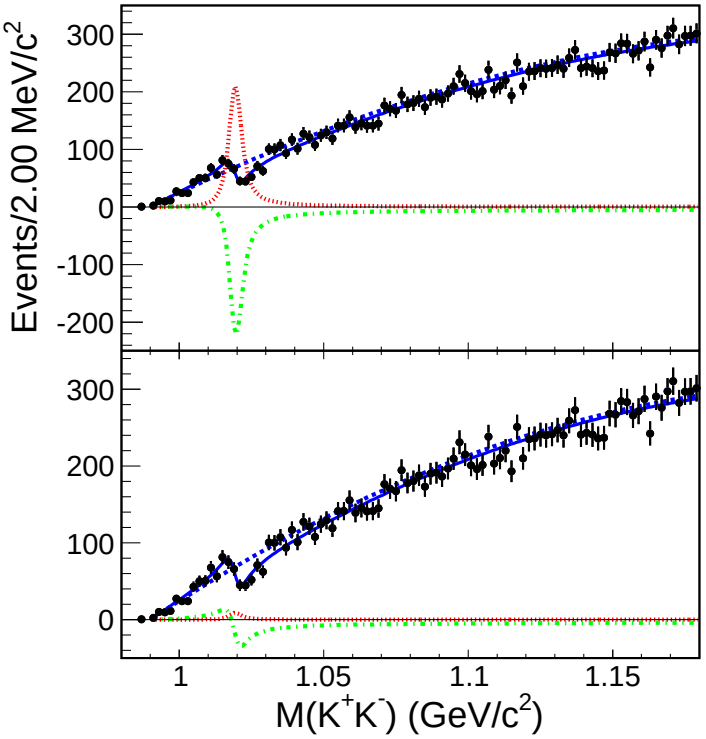

Figure 4: Fit to $M(K^+K^-)$ spectrum after sideband subtraction for Solution I (a) and Solution II (b). The red dotted curve denotes the ϕ resonance; the blue dashed curve is the non-ϕ contribution; the green dot-dashed curve represents their interference; and the blue solid curve is the sum of them.

mass spectrum as shown in Fig. 4. It can be interpreted as interference of $J/\psi \to \phi\pi^0$ with other processes decaying to the same final state. The fit yields two possible solutions and thus two branching fractions, $[2.94 \pm 0.16(\text{stat.}) \pm 0.16(\text{syst.})] \times 10^{-6}$ and $[1.24 \pm 0.33(\text{stat.}) \pm 0.30(\text{syst.})] \times 10^{-7}$ [22].

Using the measured branching fraction $\mathcal{B}(J/\psi \to \phi\pi^0)$ and $\mathcal{B}(J/\psi \to \omega\pi^0) = (4.5 \pm 0.5) \times 10^{-4}$ [16], one can extract the $\omega - \phi$ mixing parameters [20]. If $\omega - \phi$ are mixed ideally, namely $\theta_V = \theta_V^{\text{ideal}} \equiv \arctan\frac{1}{\sqrt{2}}$, the nonet symmetry breaking strength is $\delta_E \equiv r_E - 1 = (+21.0 \pm 1.6)\%$ or $(-16.4 \pm 1.0)\%$ ($(+3.9 \pm 0.8)\%$ or $(-3.7 \pm 0.7)\%$) for Solution I (II). On the other hand, we obtain $\phi_V \equiv |\theta_V - \theta_V^{\text{ideal}}| = 4.97^\circ \pm 0.33^\circ$ ($1.03^\circ \pm 0.19^\circ$) for Solution I (II) assuming nonet symmetry. However, ϕ_V is found to be 3.84° from the quadratic mass formulae [16] and $3.34^\circ \pm 0.09^\circ$ from a global fit to the radiative transitions of light mesons [23]. The ϕ_V values do not agree with either solution. This is the first indication that nonet symmetry [20] is broken and the doubly OZI-suppression process contributes in J/ψ electromagnetic

decays.

6 Summary

Using $\psi(3686)$ decays of 106 million, a sample of 1.31 billion J/ψ events and $\psi(3770)$ data of 2.9 fb^{-1} integrated luminosity, many analysis are performed. Exclusively baryonic decays of the $\psi(3770)$ are searched for, but no significant signals are observed, and the upper limits for the branching fractions are set for these decays. For the radiative transition $\psi(3770) \to \gamma\eta_c(2S)$, the $\psi(3770)$ transition to χ_{cJ}, isospin violation decay $\chi_{c0,2} \to \pi^0\eta_c$, the $C-$parity violation decays $J/\psi \to \gamma\gamma, \gamma\phi$ are searched for, but no significant signals are observed, and upper limits are set for these decays. The decays of $\psi(3770) \to \gamma\chi_{c1}$ and $J/\psi \to \pi^0\phi$ signals are observed. These measurements provide more information on the charmonium structure, and the isospin and C-parity violation in the charmonium decays.

ACKNOWLEDGEMENTS

This work is partly supported by the National Natural Science Foundation of China under Grants No. 11375205.

References

[1] J. L. Rosner, Phys. Rev. D **64**, 094002 (2001).

[2] P. A. Rapidis et al., Phys. Rev. Lett. **39**, 526 (1977);
W. Bacino et al., Phys. Rev. Lett. **40**, 671 (1978).

[3] M. Ablikim et al. (BES Collaboration), Phys. Rev. D **76**, 122002 (2007);
M. Ablikim et al. (BES Collaboration), Phys. Lett. B **659**, 74 (2008);
M. Ablikim et al. (BES Collaboration), Phys. Rev. Lett. **97**, 121801 (2006);
M. Ablikim et al. (BES Collaboration), Phys. Lett. B **641**, 145 (2006).

[4] M. Ablikim et al. (BES Collaboration), Phys. Rev. D **87**, 112011 (2013).

[5] G. Li and Q. Zhao, Phys. Rev. D **84**, 074005 (2011).

[6] M. Ablikim et al. (BES Collaboration), Phys. Rev. D **89**, 112005 (2014).

[7] Y.-B. Ding, D.-H. Qin and K.-T. Chao, Phys. Rev. D **44**, 3562 (1991);
J. L. Rosner, Phys. Rev. D **64**, 094002 (2001);
E. J. Eichten, K. Lane and C. Quigg, Phys. Rev. D **69**, 094019 (2004);
T. Barnes, S. Godfrey and E. S. Swanson, Phys. Rev. D **72**, 054026 (2005).

[8] M. Ablikim et al. (BES Collaboration), Phys. Rev. D **91**, 092009 (2015).

[9] T. E. Coan et al. (CLEO Collaboration), Phys. Rev. Lett. **96**, 182002 (2006).

[10] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. D **86**, 092008 (2012).

[11] F.-K. Guo, C. Hanhart, and U.-G. Meiβner, Phys. Rev. Lett. **103**, 082003 (2009); F.-K. Guo, C. Hanhart, and U.-G. Meiβner, Phys. Rev. Lett. **104**, 109901 (2010).

[12] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. D **91**, 112018 (2015).

[13] M. B. Voloshin, Phys. Rev. D **86**, 074033 (2012).

[14] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. D **87**, 012002 (2013).

[15]] Q. Lu and Y.-P. Kuang, Phys. Rev. D **75**, 054019 (2007).

[16] J. Beringer et al. (Particle Data Group), Phys. Rev. D **86**, 010001 (2012), and 2013 partial update for the 2014 edition.

[17] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. D 90, 092002 (2014).

[18] S. Okubo, Phys. Lett. **5**, 165 (1963); G. Zweig, CERN Report No. 8419/TH412, 1964; J. Iizuka, Prog. Theor. Phys. Suppl. **37**, 21 (1966).

[19] H. E. Haber and J. Perrier, Phys. Rev. D **32**, 2961 (1985); A. Seiden, Hartmut F.-W. Sadrozinski, and H. E. Haber, Phys. Rev. D **38**, 824 (1988); R. Escribano, Eur. Phys. J. C **65**, 467 (2010).

[20] H. E. Haber and J. Perrier, Phys. Rev. D **32**, 2961 (1985); A. Seiden, Hartmut F.-W. Sadrozinski, and H. E. Haber, Phys. Rev. D **38**, 824 (1988).

[21] D. Coffman et al. (MARKIII Collaboration), Phys. Rev. D **38**, 2695 (1988).

[22] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. D **91**, 112001 (2015).

[23] F. Ambrosino et al. (KLOE collaboration), J. High Energy Phys. **07**, 105 (2009).